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FATIGUE OF A514 STEEL IN BOLTED CONNECTIONS[a]

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INTRODUCTION

High strength steels, quenched and tempered, as well as low-alloy structural steels, often offer savings in cost, weight and size of a structure. However, where loads are repeatedly applied to the members fabricated of these steels, design specifications usually provide little or no advantage for their use; in most tests of structural connections of these steels, fatigue performance has not been significantly better than that of mild structural steels.

Exploratory fatigue tests of bolted ASTM A514 quenched and tempered, and ASTM A440 low-alloy structural steel joints conducted at the University of Illinois provided an increase in fatigue resistance for these steels and indicated that there was a possibility that a more complete study of fatigue behavior of such joints might lead to higher allowable stresses for bolted connections of the higher strength steels. The data also indicated that the fatigue strengths of bolted connections in these materials, based on gross area stresses, may be equal to or greater than those of as welded (weld reinforcement not removed) butt-type connections of the same materials. Thus, it would appear that the use of high strength steels in bolted structures that are subjected to repeated loadings may make possible the use of these materials to advantage.

The investigation reported herein concerns the fatigue behavior of bolted high strength connections of an ASTM A514 quenched and tempered structural

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steel. Several of the questions which establish the scope of the investigation follow.

1. What net section stresses are appropriate for the ASTM A514 quenched and tempered structural steels when used with high strength bolts and subjected to cycle variations of loading?
2. Is there a significant difference in fatigue behavior between joints fabricated with ASTM A325 and those fabricated with ASTM A490 bolts, (*a*) when the joints slip, (*b*) when there is no slip?
3. Can fatigue strengths be improved by additional tightening of the bolts after a period of service?
4. What are the effects of fatigue strengths of bolted connections of varying the ratio of net to gross section, the gage or spacing of the bolts, etc.?

With the preceding questions in mind, a program of fatigue tests was conducted which clearly defines the benefits of high strength bolting and provides data that can be used as a basis for the development of design specifications for the higher strength steels.

DESCRIPTION OF INVESTIGATION

Proportioning of Connections.—A compact double-lap butt-type joint with the center plate critical was chosen for this study. Two basic series of connections were proportioned: one for A325 bolts and the other for A490 bolts. Proportions were determined on the basis of a stress in tension of 50,000 psi (1/2 the minimum specified yield strength of the plates) and stresses in shear

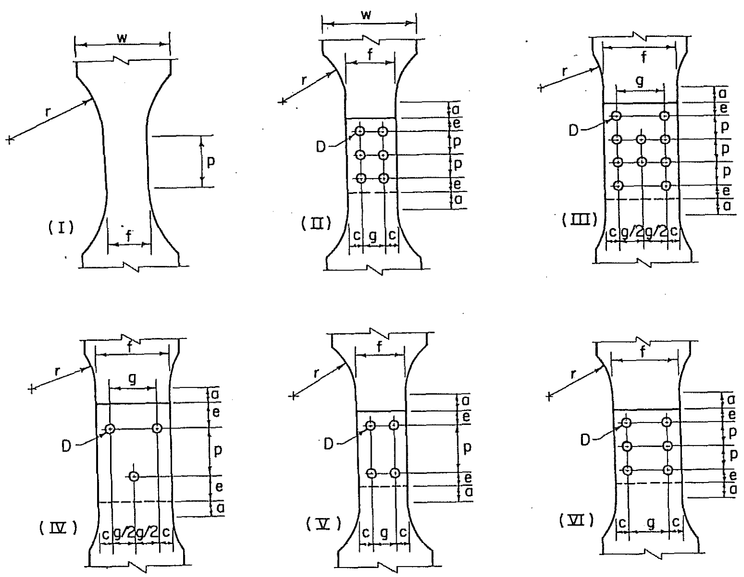

FIG. 1.—FATIGUE SPECIMEN DETAILS

of 15,000 psi for the A325 bolts and 22,500 psi for the A490 bolts. The design stresses used for the fasteners were in accordance with values recommended for friction-type joints in the 1964 Specification for Structural Joints Using ASTM A325 or A490 bolts. The value for the A490 bolts was reduced to 20,000 psi in the 1966 Specifications of the Research Council on Riveted and Bolted Structural Joints (4).[4] The design stress for the center plate was selected as being representative of the maximum values used for various structures designed for ASTM A514 steel. The dimensions of the 2 "basic" connections proportioned for these stresses are shown in Fig. 1 (Specimen II and Specimen V); in addition, the values of the T:S:B (the "tension:shear:bearing" ratio is the ratio of the net section tensile stress to the shear stress on the cross-sectional area of the bolts to the nominal bearing stress; all are nominal

TABLE 1.—FATIGUE SPECIMEN DETAILS FOR FIG. 1

Detail (1)	Specimen type (2)	Bolt type and diameter (3)	T:S:B[a] (4)	Variable Dimensions, in inches: *a* (5)	*e* (6)	*f* (7)	*g* (8)	*p* (9)	*r* (10)
I	QOP	—	—	—	—	4	—	5	9
II	Q3B, Q3T Q3R, Q3S Q3C	A 325 $\frac{3}{4}$ in.	1.00:0.30:0.69	$1\frac{1}{2}$	$1\frac{1}{4}$	$4\frac{3}{4}$	$2\frac{1}{4}$	$2\frac{1}{4}$	6
III	Q3G		1.00:0.30:0.72	$1\frac{1}{2}$	$1\frac{1}{4}$	7	$4\frac{1}{2}$	$2\frac{1}{4}$	6
IV	Q3A		1.00:1.01:2.39	$1\frac{1}{2}$	$2\frac{3}{8}$	7	$4\frac{1}{2}$	$4\frac{1}{2}$	6
V	Q4B, Q4C	A 490 $\frac{3}{4}$ in.	1.00:0.44:1.04	$1\frac{1}{2}$	$1\frac{1}{4}$	$4\frac{3}{4}$	$2\frac{1}{4}$	$4\frac{1}{2}$	6
VI	Q4G		1.00:0.45:1.06	$1\frac{1}{2}$	$1\frac{1}{2}$	$6\frac{3}{8}$	$3\frac{7}{8}$	$2\frac{1}{4}$	6

[a] Tension:Shear:Bearing ratio computed using the nominal dimensions shown above. Constant dimensions, in inches: b = 5/16-thickness of each side plate for bolted double lab butt joints; c = 1-1/4-transverse edge distance; D = 13/16-diameter of drilled hole; t = 1/2-center plate thickness of bolted joint and thickness of plain plate; and w = 9-width of pullhead.

stresses) ratio are tabulated for reference in Table 1. Also shown in Fig. 1 are three additional joint types (Specimens III, IV, and VI), and a plain plate specimen (Specimen I).

In Specimen III of Fig. 1 and Table 1, the T:S:B ratio has been kept approximately the same as in Specimen II; the dimensionally significant variable is the transverse spacing of the fasteners at the critical section. The ratio of this spacing, the gage of the fasteners, to the nominal bolt diameter is 6.0, or twice that of the basic A325 bolted joint (Specimen II). A second variation in the A325 joint is provided by Specimen IV. The number of fasteners has been reduced so that the area in shear is approximately equal to the net tensile area of the joint; this results, for a given tensile stress, in a substantial increase

[4]Numerals in parentheses refer to corresponding items in the Appendix I.—References.

in the shear and bearing stresses over those in the basic specimens. The gage to bolt diameter ratio, g/d, of these 2 joint types corresponds to an increase of approximately 12% in the theoretical efficiency of the joints over that of the basic A325 series (the theoretical efficiency is the ratio of the area of the net section to that of the gross section).

A similar variation of the g/d ratio in a series of joints using the A490 fastener provides the remaining joint type (Specimen VI). In this joint the g/d

TABLE 2.—MECHANICAL PROPERTIES OF ASTM A514-TYPE B STEEL

Heat number (1)	Thickness, in inches (2)	Mechanical Properties			
		Yield strength, in kips per square inch[a] (3)	Tensile strength, in kips per square inch (4)	Elongation in 2 inches, as a percentage (5)	Reduction in area, as a percentage (6)
66M036	$\frac{1}{2}$	118.1	126.1	34.0	58.4
84M030	$\frac{1}{2}$	122.8	125.3	28.0	52.7
71L919	$\frac{5}{16}$	124.1	130.7	24.0	52.0
69L771	$\frac{5}{16}$	122.0	130.3	21.0	46.3

[a] 0.2% offset.

TABLE 3.—CHEMCIAL COMPOSITION OF ASTM A514-TYPE B STEEL

Heat number (1)	Chemical Composition, as a percentage									
	C (2)	Mn (3)	P (4)	S (5)	Si (6)	Cr (7)	Mo (8)	V (9)	B (10)	Ti (11)
66M036	0.19	0.80	0.014	0.022	0.24	0.50	0.20	0.05	0.004	0.013
84M030	0.18	0.81	0.015	0.025	0.26	0.54	0.19	0.05	0.004	0.02
71L919	0.18	0.87	0.010	0.020	0.27	0.53	0.18	0.05	0.004	0.03
69L771	0.19	0.81	0.009	0.020	0.27	0.53	0.19	0.06	0.004	0.02

ratio was increased to 5.2 from the value of 3.0 in the basic A490 series (Specimen V).

Materials.—The plate material for all joints was from 4 heats of ASTM A514 Type B quenched and tempered steel: 2 heats of 1/2-in. plates and 2 heats of 5/16-in plates. Although the 1/2-in. critical center plates in the connections were not from a single heat, the mechanical properties and chemical compositions supplied by the manufacturer and shown in Tables 2 and 3 were similar. All plate material satisfied ASTM A514 mechanical and chemical requirements.

The high strength ASTM A325 and A490 bolts were obtained from single production lots. Each type of fastener exceeded the minimum mechanical requirements of the respective ASTM specifications for High Strength Carbon

Steel Bolts, and Quenched and Tempered Alloy Steel Bolts for Structural Steel Joints.

Bolt Installation and Specimen Preparation.—Several bolts of each type (A325 and A490) were calibrated to ascertain their load versus elongation relationships. Although the joints would be assembled using the "turn-of-nut" method, measurements of elongation were made in conjunction with the calibrations to provide an accurate means of determining the actual fastener loads and subsequent relaxation of these loads before and during the tests. Average results from the bolt calibrations are shown in Fig. 2.

The fasteners were tested by manual torquing to failure. A special solid-steel load transducer was used to measure the bolt load and simulate the stiffness of the connected parts in the joints.

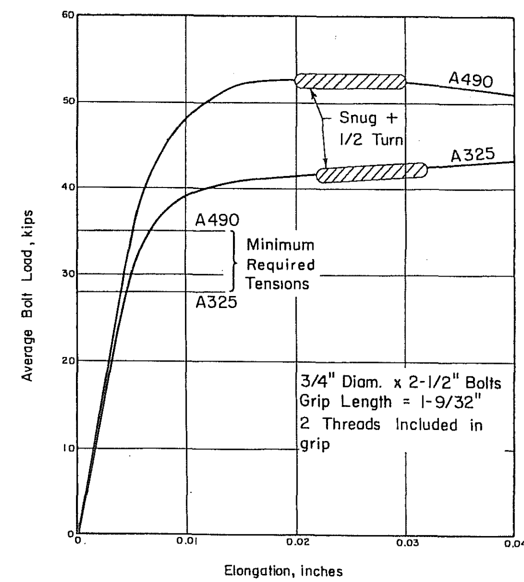

FIG. 2.—LOAD-ELONGATION BEHAVIOR FOR HIGH STRENGTH BOLTS IN TORQUED TENSION

The "snug plus one-half turn" procedure was used to install the fasteners in the joints; "snug" was selected as the load produced by 75 ft-lb of torque (approximately 5 kips to 10 kips bolt tension in 3/4-in. bolts). This method (4) of installation produced total bolt elongations ranging from 0.02 in. to 0.03 in. and corresponds to the shaded areas on the load vs. elongation curves in Fig. 2.

It may be noted that the bolt tensions at installation were 50% to 60% greater than the minimum bolt tension requirements. In general the bolt tensions obtained by this procedure are 20% to 30% above the minimum requirements. The high bolt tensions obtained in this study are due largely to the short grip of the joint and the small number of threads included in the grip. The grip of these joints was such that 2-1/2-in. long bolts were required, a length that provided only two threads in the grip. Since bolts are manufactured with a constant thread length for a given diameter of fastener and are supplied in one-quarter in. increments of length, the number of threads in the grip is variable.

To fabricate the joints, the bolt holes in the 3 plates were matched drilled and then the edges of the plates were machined to obtain the desired net section dimension. The connection was assembled with the bolt holes carefully aligned and with the mill scale in tact on the joint faying (contact) surfaces. These surfaces were cleaned with acetone prior to assembly to remove any cutting oil that remained from the drilling and machining. Exceptions to the assembly procedure occurred in seven joints, four of which were grit blasted before assembly and three of which were assembled with the bolts in bearing.

Equipment and Test Procedure.—All specimens were tested in 200 kips capacity Illinois' fatigue machines. Each specimen was fitted with slip-measurement apparatus mounted on each edge at the critical section of the joint; the movement of the center plate with respect to the outer plates was thus measured. After each specimen had been installed in the fatigue machine, it was loaded incrementally through at least one cycle of loading; those connections which slipped did so during this first cycle. The fatigue machine was then set for automatic operation. However, the load on the specimen was checked periodically, generally every 100,000 cycles to 150,000 cycles (about twice each day); in the event of a shorter expected fatigue life, this interval was shortened.

The development of a crack, which by means of a preset switch caused the machine to shut down, usually indicated that the specimen would no longer sustain repeatedly the constant maximum cyclic load. Any attempt to maintain the constant cyclic load caused complete rupture in a relatively small number of additional load cycles. The development of a crack that caused the machine to shut down was therefore used as the criterion for failure.

Analysis and Interpretation of Data.—For a given specimen type and stress ratio (ratio of minimum to maximum stress), the results of constant amplitude fatigue tests on structural steel connections (whether welded, riveted, or bolted) can be empirically related for lives between approximately 50,000 cycles and 2,000,000 cycles by the equation

$$F_n = S_N \left(\frac{N}{n}\right)^k \qquad (1)$$

in which F_n = fatigue strength at n cycles or the maximum stress that can be expected to cause failure at n cycles of loading; k = slope of the empirical straight line log-log relationship relating the maximum stress and the number of cycles to failure; and S_N = stress corresponding to failure at N cycles on the empirical curve. Thus, determination of the coordinates of a point on the best fit empirical curve, (S_N, N), and the slope, k, of that curve establishes an empirical relation (Eq. 1) between F_n and n.

An iterative technique in conjunction with Eq. 1 was used to determine a best fit empirical representation of the data. First, a value of k was assumed and fatigue strengths at 100,000 and 2,000,000 were extrapolated for each test result. To control extrapolation errors, the following arbitrary limits were employed in the extrapolation procedure:

Fatigue Strength	Range of N
$F_{100,000}$	$N \leq 600,000$
$F_{2,000,000}$	$N \geq 300,000$

Fatigue data corresponding to failure at more than 2,000,000 cycles are included directly in the average $F_{2,000,000}$ (The S-N relationship is assumed to be horizontal beyond 2,000,000 cycles). This is done because the results of numerous fatigue investigations have indicated that the fatigue strength at approximately 2,000,000 cycles provides an estimate of the fatigue limit of structural steel connections. From the average values of $F_{100,000}$ and $F_{2,000,000}$ a new value of k is computed. Continuing this iterative procedure, convergence to a value of k and an average computed fatigue strength at 100,000 cycles or or 2,000,000 cycles establishes the empirical equation which approximates the experimental data.

CONNECTIONS USING A325 BOLTS

Fatigue Behavior—Basic Series.—Three sets of basic connections of A514 steel using A325 bolts were fatigue tested under complete reversal, zero-to-

TABLE 4.—RESULTS OF FATIGUE TESTS ON A514 STEEL JOINTS USING A325 BOLTS[a]

Specimen number[b] (1)	Stress cycle on net section, in kips per square inch (2)	Cycles to failure, in thousands (3)	Computed Fatigue Strength, in kips per square inch[c]		Average Initial bolt tension, in kips (6)	Coefficient of slip, μ[d] (7)
			$F_{100,000}$ (4)	$F_{2,000,000}$ (5)		
Q3B-8	±50.0	123	52.4	—	43.5	—
Q3B-3	±50.0	111	51.2	—	43.8	—
Q3B-10	±35.0	418	48.7	24.4	43.6	—
Q3B-9	±28.0	1,561	—	26.4	43.3	—
			Average 50.8	Average 25.4		
Q3B-1	0 to +85.4	85	82.6	—	43.3	0.20
Q3B-2	0 to +80.0	84	77.1	—	43.7	0.17
Q3B-6	0 to +65.0	190	74.6	—	43.6	—
Q3B-4	0 to +53.0	727	—	42.6	43.8	—
Q3B-5	0 to +53.0	468	73.8	38.8	43.6	—
Q3B-7	0 to +40.0	2,519	—	40.0	43.6	—
			Average 77.0	Average 40.5		
Q3B-11	+40.0 to +80.0	640	—	—	43.1	—
Q3B-12	+37.5 to +75.0	1,184	—	—	43.2	—

[a] T:S:B = 1.00:0.30:0.69, g/d = 3.0.
[b] All specimens from Heat No. 66M036 (Table 2).
[c] Fatigue strengths computed using $F_n = S_N (N/n)^k$, (k = 0.231 for full reversal tests, k = 0.215 for zero-to-tension tests).
[d] Absence of coefficient of slip indicates that joint did not slip as a result of applied load.

tension, and one-half tension-to-tension loadings; these correspond to stress ratios (minimum stress/maximum stress) of -1, 0, and + 1/2, respectively. The values of minimum and maximum stresses, based on the measured net cross-sectional areas of the joints, are tabulated with the resulting number of cycles to failure in Table 4. Note that particular emphasis was placed on the zero-to-tension testing; the test results at this stress ratio form a basis for comparison with several other series of tests.

Fatigue strengths at 100,000 cycles and 2,000,000 cycles were calculated using Eq. 1. The corresponding values of k for each stress ratio are noted in the footnote to the table. Fatigue strengths were computed only where sufficient data existed to establish an empirical relation.

A number of the fatigue specimens slipped at loads less than the maximum test load. The coefficient of slip, μ, was calculated using the following formula

$$\mu = \frac{P_s}{n_f m T_b} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

in which P_s = the load causing slip of the bolted joint; T_b = the average bolt

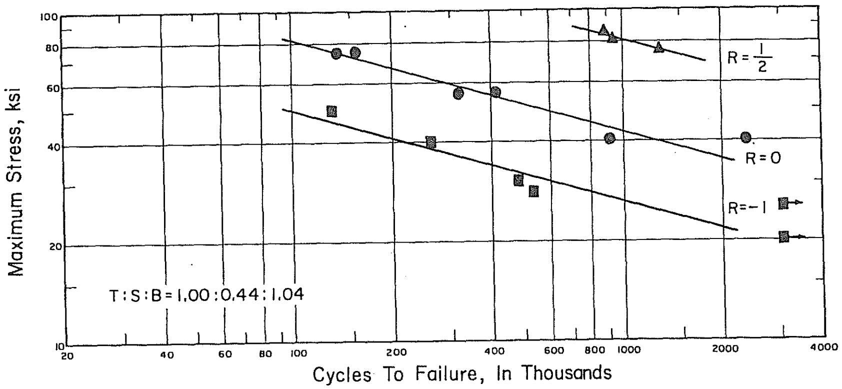

FIG. 3.—RESULTS OF FATIGUE TESTS ON CONNECTIONS OF A514 STEEL USING A325 BOLTS (NET SECTION STRESSES)

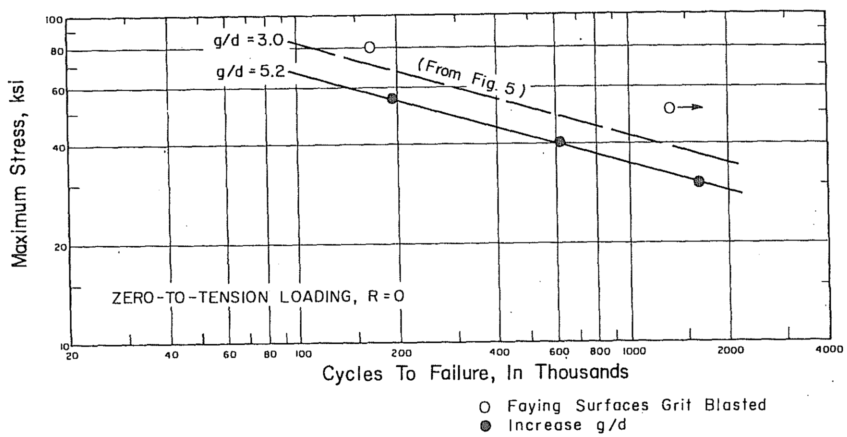

FIG. 4.—INFLUENCE OF VARIATIONS IN DESIGN AND ASSEMBLY PRACTICE ON CONNECTIONS OF A514 STEEL USING A325 BOLTS (NET SECTION STRESSES)

tension at installation; n_f = number of fasteners in the joint; and m = number of shear planes in the joint.

The fatigue test results from the basic series are shown graphically in

Fig. 3 in the form of an *S-N* curve. It is readily evident that there is little "scatter" from a straight line when maximum net section stress vs. cycles to failure are plotted on a log-log basis. The linear relations shown for R = -1 and R = 0 connect the average computed fatigue strengths at 100,000 cycles and 2,000,000 cycles recorded in Table 2. The line indicated by R = + 1/2 is an approximation from only two test results.

Effect of Bolt Installation Procedure.—Exploratory test indicated that additional tightening of the bolts subsequent to a normal installation might have a beneficial effect on the fatigue behavior of high strength steel connections. In addition, earlier fatigue studies at the University of Illinois (2) demonstrated

TABLE 5.—RESULTS OF FATIGUE TESTS ON A514 STEEL USING A325 BOLTS VARIATION OF BOLT INSTALLATION PROCEDURE[c]

Specimen number (1)	Stress cycle on net section, in kips per square inch (2)	Cycles to failure, in thousands (3)	Computed Fatigue Strength, in kips per square inch[b] $F_{100,000}$ (4)	$F_{2,000,000}$ (5)	Average initial bolt tension, in kips (6)
(*a*) Additional Tightening of Bolts Before Service					
Q3T-1	0 to +80.0	128	86.1	—	43.8
Q3T-2	0 to +55.0	485	88.3	36.0	43.3
Q3T-3	0 to +45.0	871	—	35.1	43.4
			Average 87.2	35.5	Average 43.5
(*b*) Additional Tightening of Bolts After Service					
Q3R-1	0 to +80.0	158	93.4	—	43.6
Q3R-2	0 to +55.0	327	82.2	29.8	43.5
Q3R-3	0 to +45.0	860	—	33.8	43.4
			Average 87.8	31.8	Average 43.5
(*c*) Bolts Tightened While in Bearing					
Q3S-2	0 to +55.0	465			41.9
Q3S-3[a]	0 to +55.0	460			42.4
Q3S-1	0 to +55.0	307			43.0
					Average 42.4

[a] Specimens from Heat No. 84M030; others above from Heat No. 66M036 (Table 2).
[b] Fatigue strengths computed using $F_n = S_N (N/n)^k$, (k = 0.300 for Q3T series, k = 0.339 for Q3R series).
[c] T:S:B = 1.00:0.30:0.69; g/d = 3.0.

that increased clamping force had a beneficial effect on the fatigue strengths of bolted connections of structural grade ASTM A7 steel. This information and data on the relaxation of bolt tensions after installation and during repeated loadings in fatigue tests have served as a basis for two variations which were independently introduced into the installation procedure for the basic connections using A325 bolts: (1) Approximately one month after initial bolt-up using the turn-of-nut procedure, the nuts were given an additional 30° rotation; the joint was not loaded previous to the additional tightening; and (2) following the normal turn-of-nut assembly procedure and 2,000 cycles of repeatedly loading, the nuts were given an additional 30° rotation. The results of three zero-to-tension fatigue tests for each of the preceding variations are presented in Table 5. It is evident that no significant benefit resulted from the use of these variations in bolt installation procedure.

An additional installation variable was investigated in a third series of three tests: in this case the fasteners were tightened (snug-plus-half-turn) after the joint had been slipped into bearing. The bolts were tensioned while the joints were under a tensile load of approximately 40,000 lb (7,500 psi shear stress on the fasteners) and the connections were then fatigue tested. The bolt elongations which resulted from one-half turn of the nut from "snug" were smaller

TABLE 6.—RESULTS OF FATIGUE TESTS ON A514 STEEL JOINTS USING A325 BOLTS VARIATION IN g/d, T:S:B RATIO, AND FAYING SURFACE TREATMENT

Specimen number (1)	Stress cycle on net section, in kips per square inch (2)	Cycles to failure, in thousands (3)	Computed Fatigue Strength, in kips per square inch[b] $F_{100,000}$ (4)	$F_{2,000,000}$ (5)	Average initial bolt tension, in kips (6)	Coefficient of slip, μ[c] (7)
		(a) $\frac{g}{d}$ = 6.0 T:S:B = 1.00:0.30:0.72				
Q3G-1	0 to +58.2[d]	157	65.6	—	44.0	—
Q3G-2	0 to +42.3	518	65.6	29.5	43.8	—
Q3G-4[a]	0 to +31.7	1,689+			43.5	—
Q3G-3	0 to +31.7	959+			43.7	—
			Average 65.6	29.5		
		(b) $\frac{g}{d}$ = 6.0 T:S:B: = 1.00:1.01:2.39				
Q3A-1	0 to +55.0	26	43.3	—	43.7	0.22
Q3A-2	0 to +40.0	291	48.3	—	43.7	0.20
Q3A-3	0 to +28.0	1,600	—	26.9	43.8	0.22
			Average 45.8	26.9		
		(c) $\frac{g}{d}$ = 3.0 T:S:B = 1.00:0.30:0.69 Grit Blasted Faying Surfaces				
Q3C-1[a]	0 to +80.0	274			43.8	—
Q3C-2[a]	0 to +50.0	1,293			43.6	—

[a] Specimens from Heat No. 66M036; others above from Heat No. 84M030 (Table 2).
[b] Fatigue strengths computed using $F_n = S_N (N/n)^k$, (k = 0.267 for Q3G series, k = 0.177 for Q3A series).
[c] Absence of coefficient of slip indicates that joint did not slip as a result of the applied load.
[d] + indicates that failure did not occur in the joint.

than those obtained in the bolts which were not in bearing. Note the slightly lower bolt loads tabulated with the fatigue results of Table 5.

The test results involving the 3 variations in bolt installation procedure show little effect of these variations on the fatigue behavior of the joints. A graphical comparison of these results with the basic series is shown in Fig. 4. The data fall close to the empirical curve for the results of the basic series of joints assembled with A325 bolts.

Increase in Transverse Fastener Spacing.—A reduction in the number of fasteners at the critical section of a connection results in a higher theoretical efficiency, as indicated by the ratio of the net area to gross area at the critical

section. This alteration also results in an increase in the g/d ratio, the ratio of transverse spacing to bolt diameter.

The results of fatigue tests on joints with twice the g/d ratio of the basic series, but with the same T:S (Tension:Shear) ratio, are tabulated in Table 6. These zero-to-tension test results are plotted for comparison with the basic series in Fig. 4 and, although the number of tests is limited, a reduction in fatigue strength is apparent, based on the net section stress. Note that 2 specimens in this series did not fail at the critical section of the joint, and therefore the number of cycles to failure at the net section of the joint would be greater than indicated.

Reduction in Number of Fasteners.—Current design specifications (4) allow higher design stresses in shear (i.e., fewer fasteners are required) if no restriction is placed on joint slippage. This "bearing" type of joint is not permitted for stress fluctuations involving reversals. To study the need for such a fatigue restriction for the high-strength steels, a series of 3 specimens was tested in which the number of fasteners was reduced.

In the study, 3 joints with g/d = 6.0 and T:S:B = 1.00:1.01:2.39 were tested in fatigue under zero-to-tension loadings to give an indication of how this large reduction in fasteners would affect the fatigue behavior of the joints. These results are shown in Table 6 and are plotted in Fig. 4 for comparison with the basic A325 series and the series with increased g/d. A significant reduction in fatigue strength, based on net section stress, is evident. Note that one specimen failed in the plates after only 25,000 cycles of 0 to 55,000 ksi tensile stress on the net section; however, none of the bolts showed any evidence of fatigue damage.

Grit Blasted Faying Surfaces.—The condition of irregularities in the dry mill scale faying surfaces suggested that the nonuniformity of contact and the associated low slip resistance may have had a significant affect on the fatigue performance of the joints. Since grit-blasting is often used for the surfaces of A514 steels, several joints were tested with the faying surfaces grit blasted to increase the slip resistance and possibly the fatigue strength.

The mill scale on the 1/2 in. center plate used for the tests reported herein was discontinuous, resulting in a blotchy appearance and nonuniform contact of the plates; the lap plates, in contrast had smooth and uniform surfaces; Two joints of the A325 basic series were grit-blasted with angular steel grit (SAE No. G25) before assembly and the resulting blast cleaned surfaces were free of mill scale and quite rough in texture. The results of the two zero-to-tension fatigue tests are tabulated in Table 6 and, when plotted with the average data from the basic series Fig. 4, show an increase in fatigue strength.

CONNECTIONS USING A490 BOLTS

Fatigue Behavior—Basic Series.—The second major series of tests conducted as a part of this program was concerned with the fatigue behavior of connections of A514 steel assembled with A490 bolts. The allowable shear stress for such bolts is greater than that permitted for A325 bolts and consequently fewer A490 bolts are required under comparable conditions. However, the effect of the associated increase in clamping force and the reduction in number of fasteners on the fatigue behavior of connections assembled with the A490 bolts was unknown.

The basic series in this phase (Specimen V, Fig. 1) consisted of joints of A514 steel with a T:S:B ratio of 1.00:0.44:1.04, which were assembled with A490 bolts, the specimen proportion should not be confused with the A325 basic series, (Specimen II). The results of the fatigue tests conducted on these connections at stress ratios of -1, 0 and 1/2 are presented in Table 7. A log-log plot (*S-N* curves) of the maximum net section stress vs. applied cycles to failure is shown in Fig. 5.

The A490 series of fatigue tests, when compared to the A325 series, is characterized by a slightly lower fatigue strength. The reasons for this difference are not readily evident. However, it may be noted that all but two of

TABLE 7.—RESULTS OF FATIGUE TESTS ON A514 STEEL JOINTS USING A490 BOLTS[e]

Specimen number (1)	Stress cycle on net section, in kips per square inch (2)	Cycles to failure, in thousands (3)	Computed Fatigue Strength, in kips per square inch[b] $F_{100,000}$ (4)	$F_{2,000,000}$ (5)	Average initial bolt tension, in kips (6)	Coefficient of Slip, μ[c] (7)
Q4B-7	±50.0	132	53.9	—	54.4	—
Q4B-9	±40.0	264	52.2	—	54.2	—
Q4B-8	±30.0	488	46.3	20.4	54.4	—
Q4B-10	±28.0	534	44.3	19.5	54.5	—
Q4B-12[a]	±25.0	3,028+[d]	—	25.0	54.4	—
Q4B-11[a]	±20.0	3,029+	—	—	54.4	—
			Average 49.2	21.6	Average 54.4	
Q4B-6	0 to +75.0	158	85.4	—	54.3	0.23
Q4B-5	0 to +75.0	139	82.4	—	54.2	0.21
Q4B-1	0 to +55.0	408	81.8	35.1	54.4	—
Q4B-2	0 to +55.0	320	76.4	32.8	54.2	—
Q4B-4	0 to +40.0	2,396+	—	40.0	54.3	—
Q4B-3	0 to +40.0	913	—	32.0	54.1	—
			Average 81.5	35.0	Average 54.3	
Q4B-15[a]	+43.0 to +86.0	892			54.4	0.30
Q4B-13[a]	+40.0 to +80.0	930			54.4	0.24
Q4B-14[a]	+37.5 to +75.0	1,291			54.1	0.27

[a] Specimens from Heat No 66M036; others from Heat No. 84M030 (Table 2).
[b] Fatigue strengths computed using $F_n = S_N (N/n)^k$, (k = 0.274 for full reversal tests, k = 0.282 for zero-to-tension tests).
[c] Absence of coefficient of slip indicates that joint did not slip as a result of the applied load.
[d] Indicates that failure did not occur in the joint.
[e] T:S:B = 1.00:0.44:1.04 g/d = 3.0.

the specimens of the R = -1 and R = 0 series of A490 joints had center plates from a different heat of steel than that used for the A325 series. In addition, higher shear and bearing stresses (nominal stresses) and 25% higher bolt tensions existed in the connections. Furthermore, some variation in the behavior of the 2 basic series can be attributed to the normal scatter which exists in fatigue test results and the averaging technique used to obtain the empirical approximation of the behavior.

Variation in Transverse Fastener Spacing.—A series of three connections with a T:S:B ratio approximately equal to that of the basic A490 series, but with an increased transverse spacing of the fasteners at the critical section

(g/d = 5.2), were fatigue tested under zero-to-tension loadings. The results in Table 8 (plotted in Fig. 6) show a reduction in fatigue strength, when compared to the basic A490 series. Similar results were indicated earlier for a variation of g/d in connections using A325 bolts.

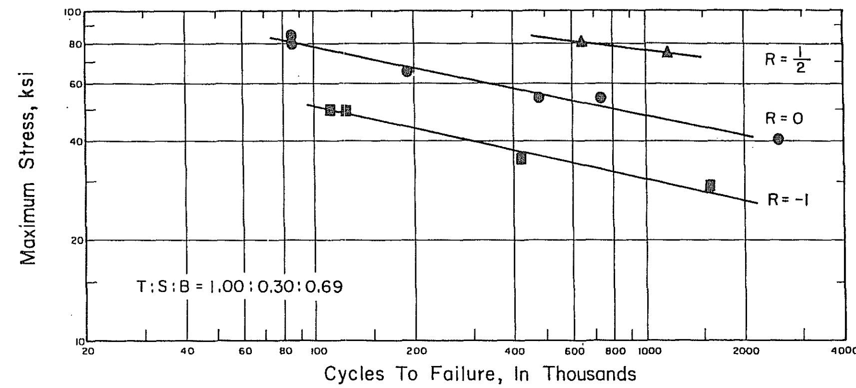

FIG. 5.—RESULTS OF FATIGUE TESTS ON CONNECTIONS OF A514 STEEL USING A490 BOLTS (NET SECTION STRESSES)

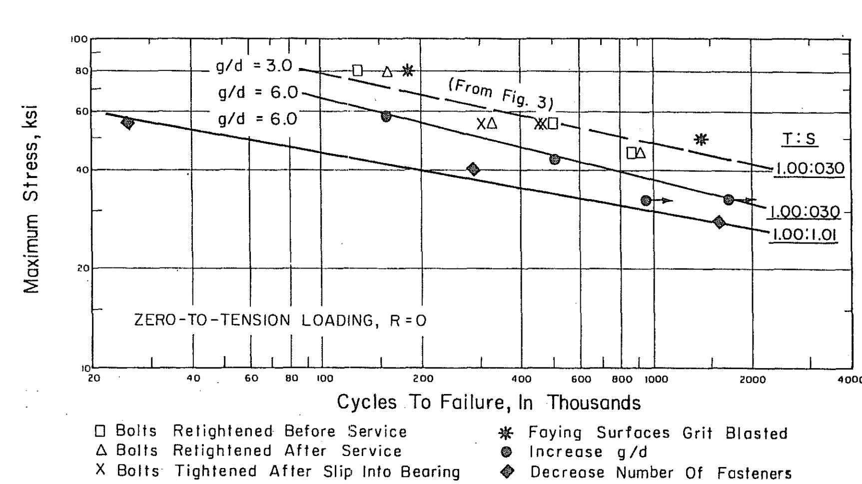

FIG. 6.—INFLUENCE OF VARIATIONS IN DESIGN AND FABRICATION PRACTICE ON CONNECTIONS OF A514 STEEL USING A490 BOLTS (NET SECTION STRESSES)

Grit Blasted Faying Surfaces.—In the study, 2 connections from the basic A490 series were grit blasted before assembly; a treatment identical to that previously described for A325 joints. The results in Table 8 reinforce the indication from the A325 results that grit blasting of the faying surfaces increases the resistance to fatigue failure. The four test results for joints which were grit blasted before assembly and in which either A325 or A490 bolts were used, are consistent and show a marked increase in fatigue performance over the joints with dry mill scale surfaces.

OBSERVATION OF BEHAVIOR AND EXAMINATION OF RESULTS

To consider the fatigue phenomenon in terms of only the stress cycle and the number of applied cycles to cause failure is not sufficient. It is essential to observe also the performance of the joints during testing and to study the resulting fatigue fractures for a better understanding of the behavior and how it is related to the various joint parameters. Several such observations will be made in conjunction with the following examination of results.

Fatigue cracks initiated on the faying surface of the center plates at or near the critical section; Four photographs of fractured specimens are shown in

TABLE 8.—RESULTS OF FATIGUE TESTS ON A514 STEEL JOINTS USING A490 BOLTS VARIATION IN g/d AND FAYING SURFACE TREATMENT

Specimen number	Stress cycle on net section, in kips per square inch	Cycles to failure, in thousands	Computed Fatigue Strength, in kips per square inch[b]		Average initial bolt tension, in kips	Coefficient of slip, μ[c]
			$F_{100,000}$	$F_{2,000,000}$		
(1)	(2)	(3)	(4)	(5)	(6)	(7)
(a) $\frac{g}{d}$ = 5.2 - T:S:B 1.00:0.45:1.06						
Q4G-1	0 to +55.0[d]	195	66.4	—	54.3	0.20
Q4G-2	0 to +40.0	622	—	28.8	54.2	—
Q4G-3	0 to +30.0	1,650	—	28.4	54.3	—
			Average 66.4	28.6		
(b) $\frac{g}{d}$ = 3.0 - T:S:B 1.00:0.44:1.04, Grit Blasted Faying Surfaces						
Q4C-2[a]	0 to +80.0	165			54.4	—
Q4C-1[a]	0 to +50.0	1,332+			54.1	—

[a] Specimen from Heat No. 66M036, others from Heat No. 84M030 (Table 2).
[b] Fatigue strengths computed using $F_n = S_N (N/n)^k$, (k = 0.281 for Q4G series).
[c] Absence of coefficient of slip indicates that the joint did not slip as a result of the applied load.
[d] + indicates that failure did not occur in the joint.

Fig. 7. These fractures were completed statically after fatigue failure. Note that the points of initiation of fatigue cracks are generally located at the intersection of the crescent shape fracture surfaces and the surface of the plate; the precise point of initiation is usually near the center of the line formed by this intersection. In a number of cases, cracks initiated at a bolt hole, near the minimum net section of Fig. 7(c); however, there was no evidence of internal crack initiation, the cracks all initiated at the surface of the plates.

The fretting or rubbing of the plates was noticeable during fatigue testing; powdery rust worked from between the plates as testing progressed. Study of the plates before and after testing indicated that the majority of this rust resulted from pulverizing of the mill scale on the faying surfaces. This phenomenon was present to a lesser extent on the grit blasted specimens which indicated a more severe galling of the base metal.

A tendency for gross section crack initiation was observed in the basic

A490 series, Fig. 7(b); however, gross section initiations were also found in the A325 specimens, e.g., Fig. 7(d) (T:S:B: = 1.00:1.01:2.39).

It is evident from observations of the fractures that the fatigue failures generally initiated in areas with the following characteristics: (1) High contact pressures (normal to the faying surfaces) resulting from the preload in the bolts; (2) high stress in the plane of the plate resulting from the stress raising effect of the bolt holes; and (3) differential movement of the adjacent plates (producing fretting) evidenced by polished appearance of certain areas on faying surface; these small differential movements should not be confused with major slip of the joint.

Fretting appears to be a prime contributing factor since in nearly all fatigue failures noticeable fretting occurred at the points of crack initiation. Discontinuities of the mill scale on the center plate influenced the location of the

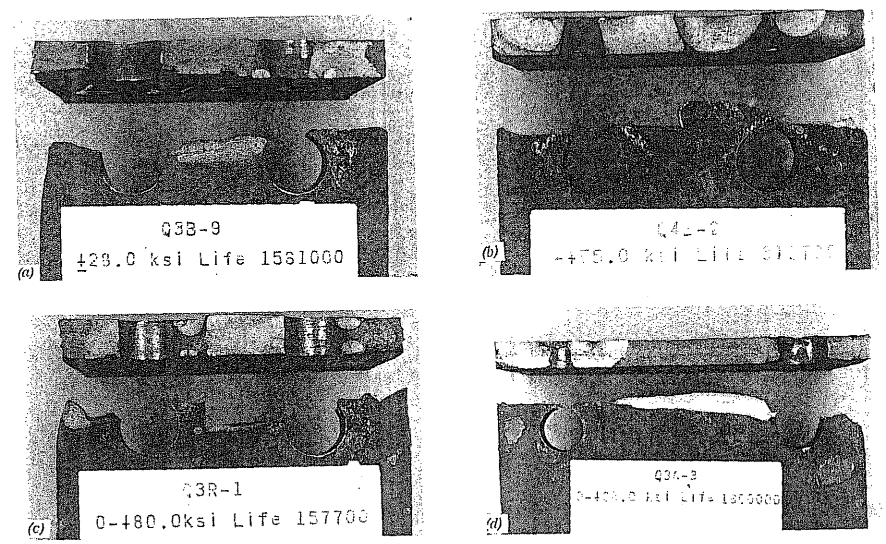

FIG. 7.—FATIGUE FRACTURES OF A514 STEEL IN BOLTED CONNECTIONS: (a) SPECIMEN Q3B-9; (b) SPECIMEN Q4B-2; (c) SPECIMEN Q3R-2; (d) SPECIMEN Q3A-3

fretting damage since the plates would be in nonuniform contact and rub (fret) where the mill scale was present. The severity of the fretting was also a function of the magnitude of the applied loads, the stress ratio, and the clamping force provided by the bolts.

Bolt tension or clamping force has been shown to relax somewhat after installation (1). The relaxation normally experienced is on the order of 5% of the initial clamping force. However, additional relaxation of the bolt tension during cyclic loading was experienced; this relaxation was based on periodic elongation measurements taken on the bolts during the fatigue tests. The total change in elongation, from the time of installation and throughout cyclic loading indicated that the bolt tension loss was rarely more than 10% of the initial tension. Relaxations as high as 20% of the initial bolt tension were reported in fatigue tests for bolted connections of ordinary structural grade steel (1). Another interesting observation is that the amount of relaxation seemed to be independent of the faying surface condition, as received (mill scale) or grit blasted.

Also of importance in the fatigue testing were the low coefficients of slip recorded for those specimens which slipped during application of the first cycle of load. For these specimens the average coefficient of slip was 0.22, a value considerably below the 0.35 often assumed for bolted structural connections of ordinary structural steel.

Table 9 provides a comparison of the fatigue performance of the bolted connections of A514 steel to the performance of the A514 plain plate material and transverse butt-welded connections (reinforcement on) of A514 plate (2).

TABLE 9.—COMPARISON OF FATIGUE STRENGTHS OF MEMBERS AND CONNECTIONS OF A514 STEELS

Type of member or connection	Stress ratio, R	Fatigue Strength, in kips per square inch		Ratio of Fatigue Strength to That of Plain Plate at:	
		$F_{100,000}$	$F_{2,000,000}$	100,000	2,000,000
(1)	(2)	(3)	(4)	(5)	(6)
Plain plate, as rolled (2)	-1	53	28	1.00	1.00
(average values)	0	89	41	1.00	1.00
	+1/2	110	57	1.00	1.00
Transverse butt welds,[a]	-1	32	16	0.60	0.57
as welded (2)	0	49	25	0.55	0.63
(average values)	+1/2	96	43	0.87	0.75
Bolted connections, using	-1	50.8	25.4	0.96	0.91
A325 bolts T:S:B =	0	77.0	40.5	0.87	0.99
1.00:0.30:0.69	+1/2	—	70.0	—	1.23
(net section stresses)					
Bolted connections, using	-1	49.2	21.6	0.93	0.77
A490 bolts T:S:B =	0	81.5	35.0	0.92	0.85
1.00:0.44:1.04	+1/2	—	70.0	—	1.23
(net section stresses)					

[a] As welded, reinforcement on.

The average experimental results for stresses to cause failure at 100,000 cycles and 2,000,000 cycles are compared for stress ratios R = -1, 0, and + 1/2. However, insufficient data were available for bolted joint tests at R = 1/2, to provide a comparison at 100,000 cycles. The bolted connection results show higher fatigue strengths than the transverse butt-welded connections and fatigue behavior nearly equivalent to that of plain plate specimens. Note that fatigue strengths for the A490 bolted joints are generally lower than for the A325 bolted joints; the slight variation of base metal properties, the joint proportioning, the magnitude of bolt clamping force and the normal scatter of fatigue tests are cited as possible reasons for this variation.

The plain plate test results shown in Table 9 were performed using specimens similar in shape to Specimen I, Fig. 1, but are the average results reported by Haaijer (2) for tests on various thicknesses and heats of A514 plate performed at the University of Illinois, Lehigh University and the U.S. Steel Applied Research Laboratory.

FATIGUE DESIGN

Several of the principal structural steel design specifications are currently being revised to include provisions of allowable static and fatigue design stresses for the higher strength low alloy and quenched and tempered alloy steels. The AASHO (American Association of State Highway Officials) Specification (5) currently provides for the use of low alloy ASTM A440 and A242 steels and specifies that the fatigue design stresses be obtained through the use of the following

$$F_r = \frac{k_1 f_{ro}}{1 - k_2 R} \qquad (3)$$

in which F_r = the maximum allowable design stress for steel subjected to fatigue, R = the stress ratio and k_1 is obtained from

$$k_1 = 1.0 + \alpha \left(\frac{F_u}{58,000} - 1.0\right) \geq 1.0 \qquad (4)$$

in which F_u = the minimum ultimate strength of the base metal in pounds per square inch. The values of k_2, f_{ro}, and α are specified and relate to the number of load applications and type of member or connection being designed.

Extension of the present AASHO specifications to include A514 steel without alteration provides one possibility for inclusion of the quenched and tempered steels in the specification. This extension involves substitution of F_u = 115,000 psi, the minimum allowable ultimate strength of A 514 steel, in Eq. 4. Using the values of α, k, and f_{ro} suggested by AASHO for base metal adjacent to a friction type connection, equations in the form of Eq. 3 can be obtained for

TABLE 10.—COMPARISON OF TEST RESULTS AND SUGGESTED FATIGUE DESIGN RELATIONSHIPS

Number of cycles of failure	Stress ratio, R	Fatigue strength from experimental data, in kips per square inch[a]	Suggested allowable design stress, in kips per square inch[b]	Ratio experimental design
(1)	(2)	(3)	(4)	(5)
100,000	-1	48.9	27.0	1.81
	0	77.7	41.8	1.85
	+1/2	—	55.0	—
2,000,000	-1	23.3	20.2	1.15
	0	37.9	31.4	1.21
	+1/2	70	43.3	1.61

[a] Combined data from connections using A325 and A490 fasteners at T:S:B = 1.00:0.30:0.69 and 1.00:0.44:1.04, respectively.
[b] Computed using Eqs. 5 and 6.

bolted friction-type connections in A514 steels. Of course, the fatigue design stress must always be less than or equal to the suggested basic allowable design stress of 0.55 F_y, in which F_y = the specified minimum yield point. For 100,000 cycles of applied load, this equation becomes

$$F_r = \frac{41.8}{1 - 0.55\,R}\ \text{(ksi)} \quad \ldots\ldots\ldots \quad (5)$$

and at 2,000,000 cycles

$$F_r = \frac{31.4}{1 - 0.55\,R}\ \text{(ksi)} \quad \ldots\ldots\ldots \quad (6)$$

In Table 10 the values of F_r obtained for R = -1, 0, and + 1/2 are compared with the experimental data. The experimental results represent the best

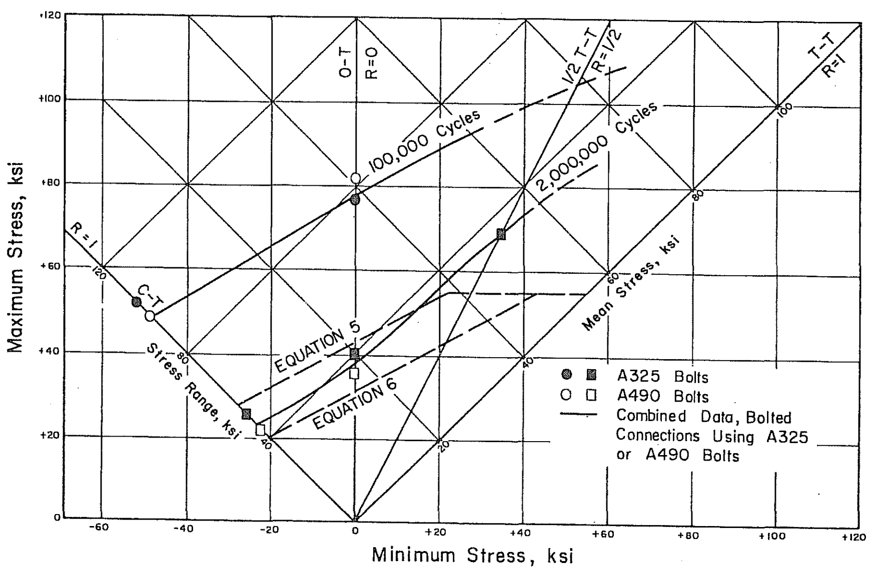

FIG. 8.—FATIGUE DIAGRAM FOR BOLTED CONNECTIONS OF A514 STEEL (NET SECTION STRESS—BASIC SERIES)

fit curve for the combined data of the A325 and A490 basic series tests. The lowest ratio of experimental stress to design stress occurs at R = -1 (full reversal) and for n = 2,000,000 cycles. The ratio in this instance is only 1.15 and would appear to be low, particularly since lower fatigue strengths were obtained when certain changes were made in the connection geometry.

A graphical display of the experimental data extrapolated for the various stress ratios is shown in the fatigue diagram of Fig. 8. The fatigue diagram is a plot of maximum versus minimum net section stress to cause failure at a specified number of cycles (stress range and mean stress are also shown). Fatigue strengths for n = 100,000 and n = 2,000,000 are shown. The data are plotted individually for each of the basic series (A325 and A490). A single curve representing the combined data of the basic series is shown superimposed. The extension of the curve into the positive stress ratio region is shown dashed because of limited amount of experimental data available. Eqs. 5 and 6 are represented by the 2 sloping dashed straight lines extended to a maximum stress of 55 ksi (the suggested basic design stress = 0.55 F_y). The small ratio (factor of safety) of experimental fatigue strength of the value computed from Eq. 6 at R = -1 is readily evident in the diagram.

CONCLUSIONS

This comprehensive investigation has provided a quantitative experimental evaluation of the fatigue performance of ASTM A514 quenched and tempered steel in bolted connections. The following conclusions are based on constant load amplitude fatigue test results and other associated measurements.

1. Extensions of present design specifications should permit higher allowable design stresses for bolted connections in quenched and tempered steels than for lower strength steels.
2. The joints in which A325 bolts, (T:S = 1.0:0.30) were used exhibited approximately the same fatigue strength as joints in which A490 bolts, (T:S = 1.0:0.45) were used.
3. An increase in the g/d ratio which is associated with an increase in theoretical efficiency causes a reduction in the fatigue strength based on the net section stress.
4. An increase in the ratio of the net tensile area of the connections to the shear area of the fasteners appears to produce a reduction in the fatigue resistance of the connected members. However, because of the limited amount of data the magnitude of this decrease cannot be clearly defined.
5. Alteration of the bolt installation procedure to regain a portion of the bolt tension lost as a result of relaxation or service loading provides no significant increase in fatigue strength.
6. Bolt tensioning while bolts are in bearing does not appreciably affect fatigue strength of the joints.
7. Unrusted quenched and tempered steel with mill scale in tact may have a low frictional resistance compared to the normally assumed value of μ = 0.35.
8. Grit blasting of the faying surfaces may produce a significant increase in fatigue strength in bolted joints of quenched and tempered steels over similar dry mill scale joints.

ACKNOWLEDGMENTS

The study reported herein is part of a research investigation on the fatigue strength of high strength steels being conducted in the structural engineering laboratory of the Civil Engineering Department, at the University of Illinois in Urbana, Illinois. The investigation constitutes a part of the structural research program of the Department of Civil Engineering under the general direction of N. M. Newmark, Head of the Department, and was sponsored by the Research Council on Riveted and Bolted Structural Joints under the Chairmanship of J. L. Rumpf.

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APPENDIX I.—REFERENCES

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APPENDIX II.—NOTATION

The following symbols are used in this paper:

d = nominal bolt diameter;
F_n = fatigue strength at n cycles or the maximum stress that can be expected to cause failure at n cycles of loading;
F_u = minimum tensile strength (5);
F_r = allowable fatigue stress (5);
f_{ro}, k_2, α = tabulated coefficients used to determine allowable stresses for material subject to repeated loading (5);
g = transverse spacing (gage) of two consecutive holes;
k = slope of the empirical straight line log-log relationship relating the maximum stress and the number of cycles to failure;
k_1 = coefficient which is function of F_u and α; see Eq. 4 and Ref. 5;
m = number of shear planes in a joint;
N, n = number of complete cycles of repeated loading to failure;
n_f = number of fasteners in a joint;
P_s = load causing slip of a bolted joint;
R = algebraic ratio of minimum to maximum stress;
S_N = stress corresponding to failure at N cycles on the empirical curve;
T_b = average bolt tension at time of installation;
T:S:B = tension:shear:bearing ratio, ratio of the net section tensile stress to the shear stress on the cross-sectional area of the bolts to the nominal bearing stress all are nominal stresses; and
μ = coefficient of slip.